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The Tapered Element Oscillating Microbalance A Monitor for Short-Term Measurement of Fine Aerosol Mass Concentration

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ABSTRACT

A new instrument for short-term monitoring of ambient aerosol fine mass concentration has been developed, based on a unique device called a Tapered Element Oscillating Microbalance (TEOM). The detector consists of a tapered hollow tube fixed at the wide end and holds an exchangeable filter cartridge at the narrow end. Air is drawn through the filter cartridge down the hollow tube. Particulates deposit on the filter cartridge. The tapered tube is maintained in continuous oscillation in a clamped-free mode whose frequency is accurately monitored. As particulates load on the filter cartridge, the frequency changes in relation to the mass added. A microprocessor-based electronics system collects and processes the data. Output is printed in a format consisting of time and aerosol concentration level in $\mu g/m^3$. The time resolution of the instrument, i.e. the time required to measure an air pollution level of 10 $\mu g/m^3$ with an accuracy of 10%, is 30 minutes. The inlet is equipped with a cyclone preseparator having a cutpoint of 2.5 μm (aerodynamic diameter), resulting in a system which provides a direct fully automated measurement of the fine mass concentration of ambient aerosol.

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CONTENTS

Abstract iii

Figures vi

Tables vii

1. Introduction 1

2. Conclusions and Recommendations 3

3. The TEOM System 4

Description 4

Monitoring options 4

Theory of operation 7

4. Technical Discussion 12

System design criteria 12

Data acquisition and evaluation 15

5. Field Measurement 17

References 19

Appendix

TEOM Operating Manual 20

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FIGURES

Number		Page
1	Tapered Element Oscillating Microbalance (TEOM) Configuration	5
2	Aerosol Monitoring Options with the TEOM	6
3	Validity of the Harmonic Approximation for the TEOM	10
4	Air Flow System	13
5	Cyclone Collection Efficiency	13
6	Air Pollution in Albany on 12/11/78 (residential area) with the TEOM Filter Unit	18

TABLES

Number		Page
1	Relation Between Mass Uptake and TEOM Frequency	8

SECTION 1

INTRODUCTION

The measurement of ambient aerosol mass concentration has been performed with a number of widely varying techniques. The most common method has been by means of gravimetric determination of the aerosol mass collected by filtration of an aerosol stream through a filter substrate. The Hi-Vol and Dichotomous Sampler are examples of this traditional approach. The method is not well suited to real-time measurement, however, since a number of hours is required for the sample collection step, and the filter samples generally then need to be transported to a central facility for the gravimetric determination.

Until now there have been two alternative methods for the short-term measurement of aerosol mass concentration: beta-attenuation and the quartz crystal microbalance (QCM). Although neither can be strictly regarded as having a real-time capability, both have the potential for performing aerosol mass measurements with a time resolution of several minutes. The beta-attenuation method is based on the decrease in the number of electrons reaching an electron counter when a thin layer of material (aerosol collected on a filter) is interposed between the counter and a radioactive source of electrons. Lilienfeld (1) has given design considerations for a mass monitor based on beta-attenuation. The QCM method utilizes the piezoelectric effect, with which the mass of aerosol deposited on an oscillating quartz crystal is inferred from the measured frequency change of the crystal. Problems with the QCM method have included (1) difficulty in depositing aerosol on the crystal surface, (2) uncertainty of aerosol adhesion due to large surface accelerations, (3) small dynamic range, (4) dependence of the frequency change on the surface profile of the deposited mass, and (5) erratic behavior in conditions of varying humidity. Lundgren et al (2) have described the QCM, its problems and possible solutions. Both the beta-attenuation and QCM approaches have been employed in commercially available instruments. An evaluation of several of these instruments has been given by Fairchild et al (3).

This report describes a novel instrument for the short-term monitoring of fine aerosol mass concentration, which is based on the newly developed Tapered Element Oscillating Microbalance (TEOM). Like the QCM, mass is determined through measurement of frequency change. In nearly all other respects, however, the TEOM is distinctly different from the QCM, and is intended to avoid the previously listed difficulties of the latter. The principle and various

applications of the TEOM have been described previously (4). The TEOM has been assigned U.S. Patent No. 3,926,271.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

The Tapered Element Oscillating Microbalance (TEOM) represents a new, unique instrument capable of short-term aerosol fine mass concentration measurement. The TEOM measures the mass of collected particulates, independent of their composition, atomic number, optical properties, shapes, or any other particle property. While appearing to be very promising, field experience needs to be accumulated with the TEOM to confirm its expected usefulness in ambient air monitoring. The field experience should include intercomparisons with existing short-term monitors such as beta-attenuation and QCM devices, and integrating nephelometers, as well as conventional long-term samplers such as the dichotomous sampler.

Exchangeable filter cartridges made from membrane filter material are presently used. It is recommended that in the future a multi-stage filter be developed consisting of an outer layer of depth filter material combined with an inner membrane filter. In this way the major portion of the deposited mass is trapped in the volume of the fibrous depth filter, drastically slowing down the clogging of the inner membrane filter. This would substantially increase filter lifetime beyond the approximate one-week lifetime in its present form.

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SECTION 3

THE TEOM SYSTEM

DESCRIPTION OF THE TAPERED ELEMENT OSCILLATING MICROBALANCE, TEOM

The active element of a TEOM consists of a tube constructed of a material with high mechanical quality factor and having a special taper. This tube is firmly mounted at the wide end while the other end supports a substrate (or filter cartridge) which can be composed of virtually any material. The tapered tube with the substrate at the free (narrow) end is set into oscillation whose natural frequency will change in relation to the mass deposited on the substrate (or filter). The sensitivity and frequency can be chosen at will by proper dimension ıg of the oscillating tapered element.

The operation of a TEOM is shown in simplified manner in Figure 1. The tapered element is kept in oscillation by a feedback system. The oscillation of the element is converted into an electrical signal by a light-emitting diode-phototransistor combination, the output of the phototransistor being modulated by the light-blocking effect of the vibrating element.

Unlike most other microbalances, the TEOM is mechanically strong and is easily automated with data output consisting of frequency information in the 10^2 to 10^3 Hz region. Such low frequencies avoid the QCM problem of aerosol adhesion to a rapidly accelerating surface (QCM frequencies are typically 10 MHz.).

AEROSOL MONITORING OPTIONS WITH THE TEOM

Two candidate particulate collection methods, impaction and filtration, were considered for use with the TEOM. These two methods are illustrated in Figure 2. Figure 2a shows the impaction method where particulates in the air stream are impacted against a substrate (greased or ungreased) on the TEOM. Typical mass sensitivity for an impactor TEOM is in the order of 3×10^{-10}g. Classical impaction techniques, however, have well known difficulties and, as a result, a filtration TEOM unit has been developed. The filter unit was developed to represent an absolute standard (through the use of an absolute filter) for the short-term measurements of aerosol mass concentrations.

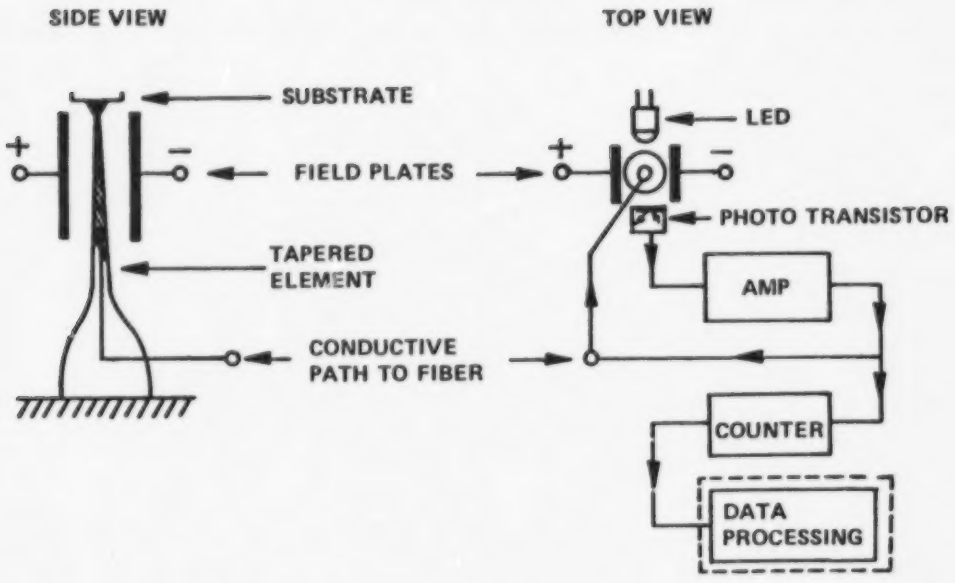

Figure 1. Tapered element oscillating microbalance (TEOM) configuration (typical).

TEOM OPERATION

1. **Electric field is set up between field plates.**
2. **Image of tapered element is projected on phototransistor.**
3. **Oscillation of element initiated electrically or mechanically produces an AC voltage output from phototransistor.**
4. **AC voltage is amplified and applied to conductive path on element which maintains the oscillation due to interaction with field set up in Step 1.**
5. **Frequency of oscillation, and hence mass on substrate, is determined by frequency counter.**

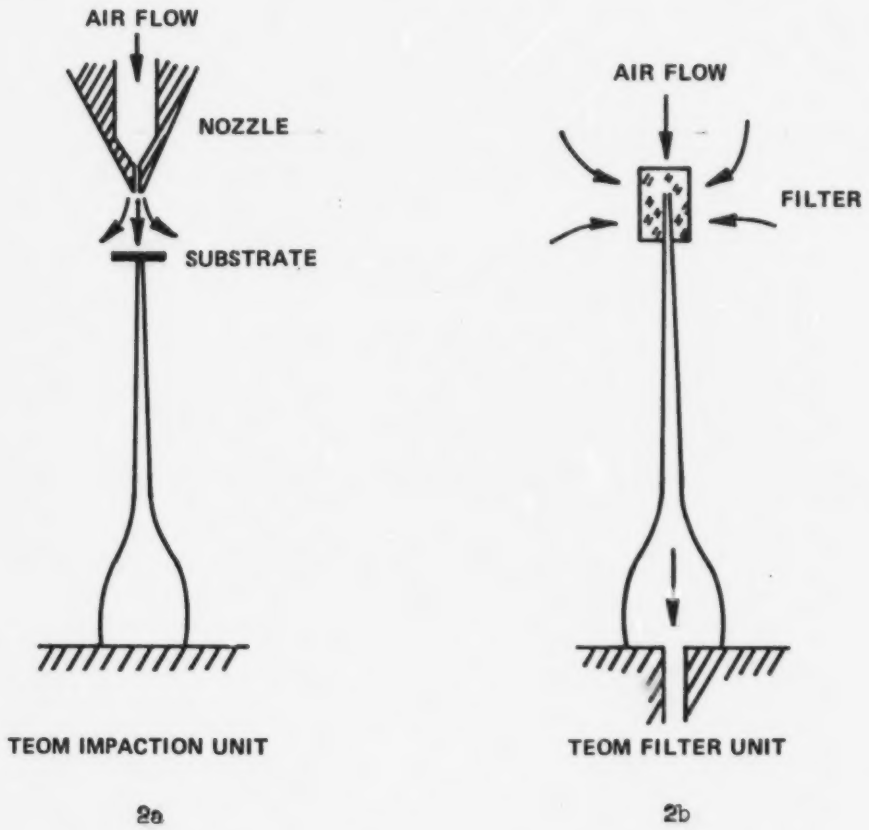

Figure 2 Aerosol monitoring options with the TEOM.

Consequently, this report will concern itself solely with the filter version of the TEOM. In this configuration, shown in Figure 2b, a filter cartridge is placed at the free (narrow) end of the hollow tapered element. Particulate-laden air is drawn through the filter, and the resulting filtered air is pumped down the hollow tube.

THEORY OF OPERATION

The TEOM is an oscillator with a high mechanical Q-factor whose frequency, as will be shown subsequently, can be adequately described with two parameters, the restoring force constant, K, and the effective mass, m, consisting of the mass of the filter, m_F, the effective mass of the tapered element, m_o, and the filter loading, Δm.

$$m = m_F + m_o + \Delta m \tag{1}$$

The relation between these quantities is given by the expression:

$$4\pi^2 f^2 = \frac{K}{m} \tag{2}$$

or

$$f^2 = \frac{K_o}{m} \quad \text{with } K_o = \frac{K}{4\pi^2} \tag{3}$$

The TEOM as a Harmonic Oscillator

A theoretical analysis of the oscillation of the tapered element in a TEOM shows that no closed form solution exists for frequency as a function of mass uptake. However, one can demonstrate conclusively by experiment that it is absolutely unnecessary to use a high powered mathematical treatment for the relationship of mass loading vs. frequency. Indeed it will be shown that for all practical purposes the TEOM can be considered a harmonic oscillator.

To prove this point an experiment with a tapered element has been carried out over a mass loading range from 30 mg to 330 mg. In the present application, a filter TEOM usually operates around a constant mass loading of approximately 100 mg with a total mass uptake during sampling of no greater than 20 mg. This is clearly well within the tested range.

The TEOM was tested using a series of masses which were gravimetrically measured. Each mass was placed on the TEOM and the resulting frequency recorded. The results of this measurement are listed in Table 1.

In Equation 3, the relation between frequency and mass for a harmonic oscillator is given in the form

TABLE 1. RELATION BETWEEN MASS UPTAKE AND TEOM FREQUENCY

Mass Added Δm (mg)	TEOM Frequency f (Hz)	f^{-2} (sec^2)
31.8	183.712	2.963×10^{-5}
48.2	160.635	3.875
64.1	144.386	4.797
82.8	130.029	5.915
112.8	114.459	7.633
157.3	99.124	10.18
267.5	77.94	16.46
330.0	70.67	20.02

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$$f^2 = \frac{K_o}{m_o + \Delta m} \tag{4}$$

where Δm is the added mass and m_o is the fixed mass of the oscillator. If Equation 4 is written in the form

$$\frac{1}{f^2} = \frac{1}{K_o}\Delta m + \frac{m_o}{K_o} \tag{5}$$

one can prove the applicability of the harmonic oscillator formulation by challenging the validity of this expression. Setting:

$$\frac{1}{f^2} = y \tag{6}$$

$$\Delta m = x \tag{7}$$

$$\frac{1}{K_o} = \mu \tag{8}$$

and

$$\frac{m_o}{K_o} = n \ , \tag{9}$$

Equation 5 can be rewritten in the linear form

$$y = \mu x + n \tag{10}$$

If the TEOM deviates from a harmonic oscillator, the linear relation as expressed in Equation 10 will not hold. The data from Table 1 are plotted in this form in Figure 3. A linear relationship is apparent. How linear this relationship is can be assessed by a least square fit of the data through the correlation coefficient, r. K_o results as the inverse slope and m_o/K_o as the 'y' intercept. The results of a least square fit of the data in Table 1 yield:

$$r = 0.9999930$$

$$K_o = 1747 \left[1 \pm 4.3 \times 10^{-3}\right] \ (g/sec^2)$$

$$m_o = 20.1 \ (mg)$$

There is no room for doubt that the harmonic approximation is perfectly adequate for the data evaluation of a TEOM.

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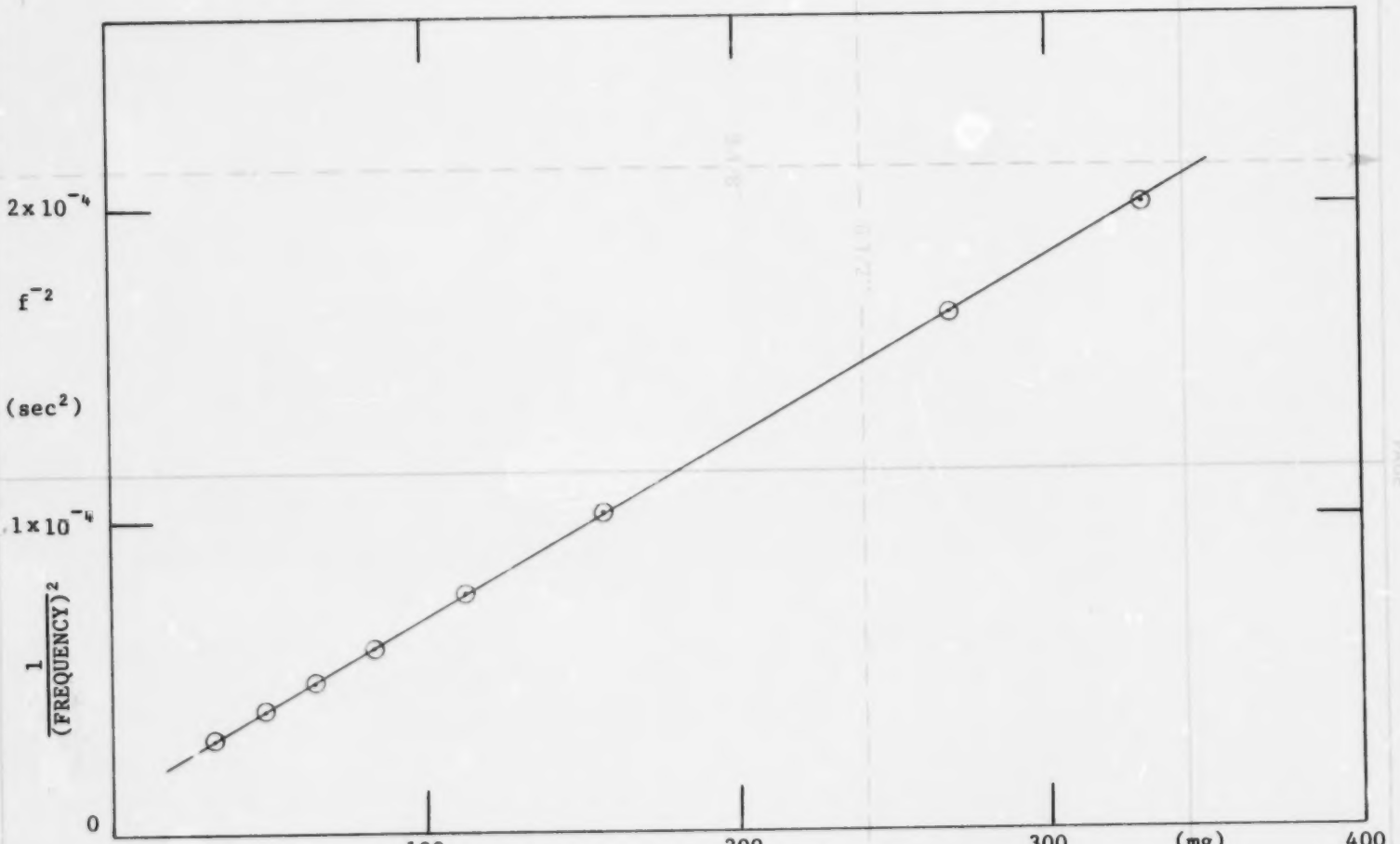

Figure 3. Validity of the Harmonic Approximation for the TEOM

Calibration Process

If a mass Δm is determined gravimetrically and added to the filter, K_o can be determined from the frequencies f_1 and f_2 where f_1 is the frequency without Δm and f_2 is the frequency with the filter loading mass Δm. It is

$$f_1^2 = \frac{K_o}{m_F + m_o} \tag{11}$$

$$f_2^2 = \frac{K_o}{m_F + m_o + \Delta m} \tag{12}$$

From these two equations K_o for a particular device can be calculated:

$$K_o = \frac{\Delta m}{(1/f_2^2) - (1/f_1^2)} \tag{13}$$

Mass Measurements

If the TEOM is oscillating to start with at the frequency of f_a and exhibits the frequency f_b after a mass uptake, Δm can be obtained as a function of f_a, f_b, and K_o. It is

$$f_a^2 = \frac{K_o}{m} \tag{14}$$

$$f_b^2 = \frac{K_o}{m + \Delta m} \tag{15}$$

Elimination of m leads to

$$\Delta m = K_o (1/f_b^2 - 1/f_a^2) \tag{16}$$

As is evident in Equation 16 the relation between frequency and mass uptake is not linear. Note that Equation 16 is independent of the filter mass, m_F, and the effective mass, m_o, of the oscillating tapered element.

In successive mass measurements, the total mass of the system is implicit in the starting frequency, f_a. As a result, the new frequency, f_b, at the end of a measurement period, is different from f_a only as a result of the mass uptake, Δm, added during the measurement period.

SECTION 4

TECHNICAL DISCUSSION

SYSTEM DESIGN CRITERIA

In order for the TEOM to perform accurately and reliably, a number of criteria had to be met.

Cut Point and Air Flow

In the instrument described in this report, a cut point of 2.5 μm has been designated so that the aerosol measurements obtained with the finished unit represent the fine particle concentration in the air. In order to achieve this cut point, a cyclone preseparator is utilized.

In particular, Cyclone IV of the EPA-SRI five stage cyclone chain was chosen. To achieve the desired cut point, a flow rate of 7.1 l/min is required. A diagram of the air flow system for the TEOM is shown in Figure 4, and the characteristics of the cyclone are shown in Figure 5. (The cyclone performance curve in Figure 5 is taken from Smith, W.B. and Wilson, R.R., Development and Laboratory Evaluation of a Five-Stage Cyclone System, EPA-600/7-78-008, 1978.)

In this system, air enters the air inlet pipe and particulates are separated by the cyclone. Fine particles continue into the TEOM where they are filtered out by the filter cartridge, and the filtered air proceeds down the tapered element to the flow controller. A mechanical flow controller of the type that maintains a constant Δp across a fixed aperture is utilized.

Temperature Stabilization

A number of components in the TEOM system have a temperature sensitivity which could produce a frequency change. The most sensitive component is the tapered element itself. Additionally, the photo-optics of the feedback system can also result in a frequency shift if their output changes with temperature. Consequently, the entire housing surrounding the TEOM is designed with a heater element so that it can be temperature stabilized. A temperature control circuit utilizing a thermistor in a bridge circuit has been incorporated. Since air is passing through the tapered

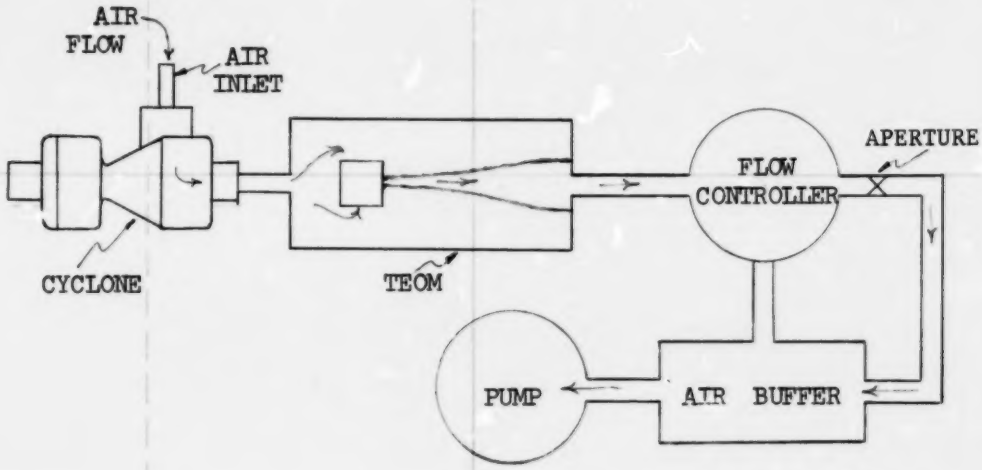

Figure 4. Air flow system.

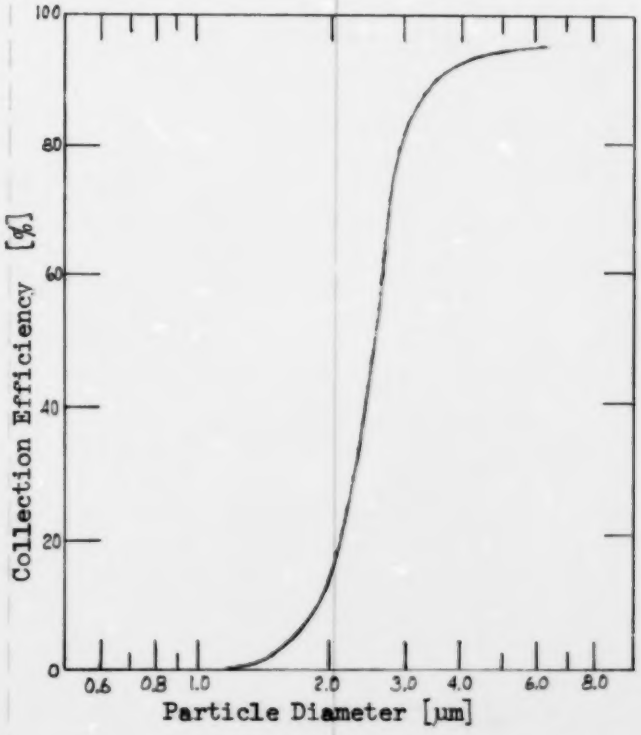

Figure 5. Cyclone collection efficiency: 7.1 ℓ/min.

element, it is necessary to temperature stabilize the air stream as well. This is achieved by heating the inlet pipe and cyclone preseparator with a second temperature control circuit whose reference temperature is the TEOM housing, and whose sensor thermistor is in the air stream between the cyclone exit and TEOM entrance.

Short term temperature stability of better than 10^{-2} C (1 hour time duration) has been achieved with the system. This corresponds to a frequency change of less than 0.1 mHz which results in less than 0.3 $\mu g/m^3$ error over a 1/2 hour monitoring period.

Humidity Suppression

Performance of a usual microbalance suffers from apparent mass changes in the collected aerosol mass caused by ambient humidity changes. This is avoided in the TEOM system by the combination of a hydrophobic filter cartridge and by running the system at an elevated temperature of approximately 60°C.

Filter Requirements

A suitable filter for the system must be optimized in a number of respects.

1. Minimum weight - The sensitivity of a TEOM is inversely proportional to the total mass involved in the vibration. Since the filter mass represents the major contribution to the total oscillating mass, a minimum filter mass is desirable.

2. Maximum surface area - To provide for the appropriate flow rate and as long a filter life as possible, surface area must be maximized.

3. Hydrophobic - To reduce effects of humidity on the measurements, hydrophobic materials must be used in the construction of the filter.

4. Exchangeability - All the above factors must be designed in the filter, in combination with an easy and rapid means of filter exchangeability.

A solution fulfilling the filter requirements has been achieved by the utilization of a pleated membrane filter whose final form is a cylindrical cartridge of approximate dimension of 7 mm diameter by 7 mm high. It is mounted on the tapered element by a press fit of a conical insert at the interior of the cartridge to a matching conical support at the end of the tapered element.

Operational Requirements

From the user's standpoint, there are a number of considerations

involved in making the instrument a practical device. The instrument must be designed to be fully automatic so that once initiated it will continuously monitor and record the aerosol concentration level with no further operator assistance until a filter change is necessary. The instrument should signal when a filter change is required, and the filter change operation should be exceptionally simple and rapid. The data output should provide a continuous record of time and aerosol concentration level directly in $\mu g/m^3$. All these requirements have been implemented in the present version of the TEOM system.

DATA ACQUISITION AND EVALUATION

The data acquisition, time keeping functions, and computations are accomplished by the utilization of a microprocessor. The microprocessor receives information on the oscillation of the TEOM by means of a period measurement counter.

Determination of the TEOM Oscillation Period, τ

Equation 16 can be rewritten in the form:

$$\Delta m = K_o (\tau_b^2 - \tau_a^2) \qquad (17)$$

where

$$\tau_i = f_i^{-1}, \quad (i = a,b) \qquad (18)$$

The time period τ_i is determined in the following manner. First a gate is opened at a zero crossing of the phototransistor output, which represents the TEOM oscillation. After a number of TEOM oscillations, N, occurs (typically N = 1024) the gate closes at the appropriate zero crossing of the phototransistor signal. The time interval between the opening and closing of the gate, Δt_i, is therefore

$$t_i = N\tau_i \ . \qquad (19)$$

The time period Δt_i is measured by a high frequency clock whose frequency, f_c, is typically 2.5×10^5 Hz. The time period, Δt_i, is therefore represented by the number of counts, C_i, of the high frequency clock during the gating time.

$$C_i = \Delta t_i f_c = N\tau_i f_c. \qquad (20)$$

Therefore:

$$\tau_i = \frac{C_i}{Nf_c} \qquad (21)$$

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Substituting Equation (21) into (17) yields:

$$\Delta m = \frac{K_o}{N^2 f_c^2} (C_b^2 - C_a^2) \qquad (22)$$

Microprocessor Functions

Every gated time interval results in a number, C_ν, which is entered into a register with n locations. Typically, n = 50. At the arrival of a new point entering a filled register chain, the oldest entry is dropped. Therefore, the register chain contains continuously updated information about the most recent 50 data points. A running average, $\langle C \rangle$, of these data points is maintained. $\langle C \rangle$ is updated every time interval, Δt, which is typically according to Equation (19):

$$\Delta t = N\tau_i = (1024)\ (1/200) \approx 5 \text{ sec.}$$

Therefore $\langle C \rangle$ represents a count average over 5 sec x 50 = 250 sec, or approximately 4 minutes.

For ambient aerosol monitoring, it is desirable to obtain average particulate concentration levels over a time period of 1/2 hour or 1 hour. As a result the $\langle C \rangle$ values are retrieved for particulate concentration computations every 1/2 hour or 1 hour intervals, as selected. If $\langle C \rangle_a$ is the average of the C values at time, t_a, and $\langle C \rangle_b$ is the average at time, t_b, the mass accumulation over the time period, $t_b - t_a$ (1/2 hour or 1 hour) is according to Equation (22),

$$\Delta m_{a,b} = \frac{K_o}{N^2 f_c^2} (\langle C \rangle_b^2 - \langle C \rangle_a^2) \ . \qquad (23)$$

By dividing $\Delta m_{a,b}$ with the flow rate, F, the particulate concentration, $P_{a,b}$, is obtained.

$$P_{a,b} = \frac{\Delta m_{a,b}}{F} \left[\frac{\mu g}{m^3}\right] \ . \qquad (24)$$

These data are printed out in $\mu g/m^3$ every 1/2 hour or hour, as selected, with a corresponding clock time (based on a 24-hour clock).

SECTION 5

FIELD MEASUREMENT

Typical results of measurements with the filter TEOM unit are shown in Figure 6 which exhibits aerosol mass concentration as a function of time over one day. Data were taken in real time every 15 minutes with a flow rate of 5 ℓ/min through a Teflon membrane filter cartridge with a 1 μm pore size. The variation of the aerosol level during the course of the day is, to a great extent, related to the traffic pattern. The results were obtained with an early version of the TEOM, in which the aerosol stream and instrument were maintained at 50°C, and without a cyclone preseparator. The final version operates at a flow rate of 7.1 ℓ/min, at an internal temperature of 60°C, and with a cyclone preseparator having a 2.5 μm cutpoint.

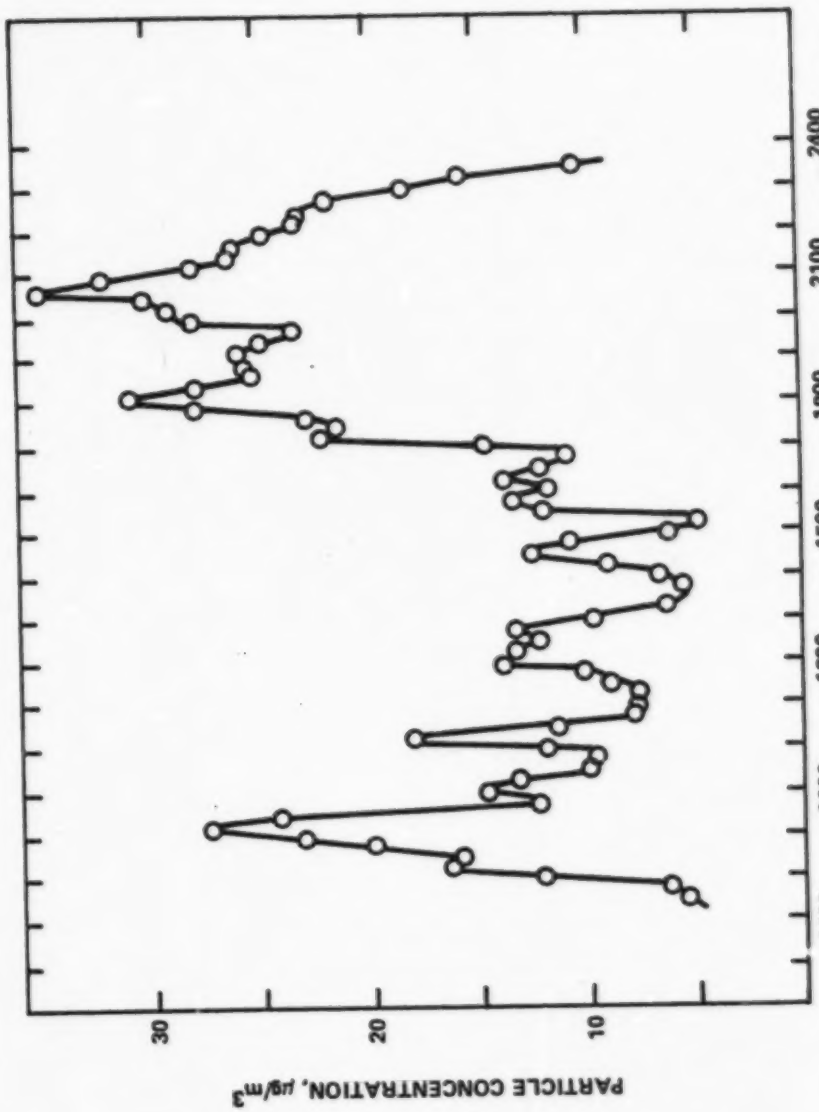

Figure 6. Air pollution in Albany on 12/11/78 (residential area) with the TEOM filter unit.

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APPENDIX

TEOM INSTRUCTION MANUAL

EPA Form 2350-4 (4-80)

(PREVIOUSLY CIN: EPA FORM 2911)

TYPING GUIDE SHEET

Instruction Manual

for the

TEOM Filter Unit

Ambient Particulate Mass Monitor

I. Description

This instrument is based on a new device called the Tapered Element Oscillating Microbalance (TEOM). The TEOM is a very sensitive mass monitor. It consists of a tapered, hollow tube which is mounted at its wide end. A filter cartridge is located at its narrow (unmounted or free) end. Particulate laden air is filtered through the filter cartridge and the filtered air is drawn through the hollow tube. The hollow tube (or tapered element) with the filter cartridge attached is maintained in mechanical oscillation through an electronic feedback system in a clamped-free mode. The frequency of oscillation is continuously monitored very accurately. As the filter cartridge loads with particulates and therefore increases in mass, the frequency of oscillation decreases. The frequency change provides a measure of the mass uptake and when combined with the flow rate the mass concentration of the sampled air can be determined.

The TEOM detector and the incoming air are both temperature stabilized to approximately 60°C to insure frequency stability and to minimize humidity effects on the aerosol measurement. A hydrophobic filter cartridge is used as well.

This unit is also equipped with an SRI-EPA Cyclone IV used as a particle preseparator, providing a cut-point at 2.5 μm.

II. Components

The total system is comprised of three basic pieces of hardware (see Fig. 1).

A. Electronics package - consists of feedback amplifier, frequency counter, control circuits, microprocessor, LED display, and printer.

B. Detector package - consists of TEOM filter unit detector, cyclone preseparator, air heater, flow controller and air buffer.

C. Pump - consists of an oilless, vacuum pump located externally from the electronics and detector package.

Peripheral accessories include:

1 Cable
1 Air hose
1 Roll of printer paper
6 Filter cartridges
1 Air inlet extension

III. Assembly and Checkout

1. Check for any shipping damage.

2. If indicator on printer reads 'E', the paper roll has vibrated loose during shipping and needs to be reset. Turn the thumbscrew counterclockwise and pull to remove the printer face and paper roll holder. Push paper roll in place and return panel in printer.

3. Open detector package. To remove cover, loosen four (4) screws on top and two (2) screws outlined in blue on bottom. Refer to Fig. 2. Carefully remove packing from around the TEOM detector but leave the white foam insulation jacket around the TEOM. Examine the three (3) rubber hose supports of the detector so that the detector suspends freely without touching the edges of the circular cutout on the front panel. Pay particular attention to the rubber hose support between the air heater and the detector, as it must both support the detector and provide a leak-tight seal between the air heater and the detector.

   Examine the three (3) miniature green connectors on the TEOM detector. One is on top toward the front of the detector; the other two are on the bottom toward the back end of the detector. Make sure they are connected securely.

   Do not attempt to open the TEOM detector.

   Check for any broken wires at the large connector in the rear of the package and inspect the air buffer for any cracks.

   After checkout, replace the detector package cover. Locate the detector package at a site where it will remain undisturbed during use and free from external vibrations.

4. Connect the electrical cable between the electronics package and the detector package.

5. Position the line switch on the vacuum pump at 'off'.

6. Check that the thumbscrew on the pressure side of the pump is screwed fully in (fully clockwise), but the thumbscrew on the vacuum side of the pump is almost entirely screwed out, counterclockwise.

7. Position the toggle switch on back of the electronics package at 'on'.

8. Put plug of vacuum pump line cord into recepticle on back of electronics package.

9. Connect hose from the vacuum port of the pump to the lower hose connector on the detector package. Locate the pump away from the detector package so that the pump vibration will not couple into the detector package.

10. Check that the main power switch in front of the electronics package is 'off' and plug in the line cord from electronics package into wall recepticle (110V 60Hz).

IV. Operating Instructions

A. Instrument warm-up

1. Turn main power switch on. Pump should not start. If it does, turn it off by its line switch. LED display should read 0000.

2. Connect a digital voltmeter to the banana plugs on the front panel. As the instrument warms up, the resistance measured at these plugs will change from approximately 10 KΩ to 2.8 KΩ in about 1 to 1½ hours.

3. After warm-up, turn pump on by its line cord switch.

4. Unscrew TEOM detector top ring.

5. Remove TEOM top plate.

6. Take a filter cartridge from its vial (reclose the vial) and gently insert the cartridge on the tapered mount on top of the TEOM oscillating element. The filter should be pushed on and rotated slightly so that it gently seats. Do not apply force. Filters should not be deformed by this process. Do not attempt to bend or produce any sideways motion on the tapered element or it may break. Also note that the air deflector in the filter chamber is quite sharp, so use care with fingers.

7. Reseat '0' ring.

8. Replace top cap.

9. Screw on top ring. Do not over-tighten.

10. Screw the thumbscrew on the vacuum side of the pump clockwise as far in as it will go. The vacuum gauge should read approximately 21" Hg. Flow rate should be approximately 7.1 l/min.

B. Keyboard Entries

1. Press blue reset button once. This allows access to the microprocessor by use of the keyboard. If when entering information as described below with the keyboard, an error is made, press 'clear' and repeat with the correct entry.

2. Press keypad numeral '1', then press 'enter'.

   Use keypads to enter the time in hours and minutes based on a 24 hour clock. Then press "enter".

   Example sequence:

   1
   Enter
   0830
   Enter

   Wait for the LED display to count up to the time entered. After it does, the display will once again read 0000.

3. Press keypad numeral '2', then press 'enter'. The time should be displayed on the LED display. If the time displayed is not the time that was entered, repeat the operation described in Step 2.

4. Press keypad '3' then 'enter'. Use keypads to enter a starting time in hours and minutes based on a 24 hour clock. This starting time is the time at which the microprocessor will start to take data. If an immediate start time is required, enter a time which is sufficiently advanced from the clock time indicated to be completed, e.g. two minutes.

   Example sequence:

   3
   Enter
   0832
   Enter

5. Next, press '7' then 'enter' to enter the filter calibration constants. Each filter is supplied with its own calibration constants as indicated on each filter vial.

   Example sequence:

   7
   Enter
   0022
   Enter
   6250
   Enter
   0000
   Enter

6. To obtain printouts every $\frac{1}{2}$ hour, next employ the following sequence:

   9
   Enter
   0001
   Enter

   If hourly printouts are desired, skip this step entirely and proceed to Step 7.

7. Next press '5', then 'Enter'.

   This initiates the microprocessor program and prevents any further keyboard entries. The display will initially show 0000. The microprocessor can be stopped and keyboard entry regained by pressing the blue reset button. If this is done, the entry sequence described in Steps 4 - 7 must be redone. The microprocessor retains the time entry unless power is turned off.

   If power is interrupted at any time, all keyboard entries must be redone.

C. Obtaining Measurements

After completing the keyboard entries, the display will show 0000. If hourly printouts are selected, when the clock reaches whole hour times printouts occur of time in hours and measurement in ug/m^3. Printouts occur every hour on the hour, and the measurements correspond to the average over the hour between the most recent and previous printout. A printout of 1400 hours and 20 ug/m^3 means that an average level of 20 ug/m^3 occurred during the time interval of from 1300 to 1400 hours. For this reason it may be desirable, when entering the time by the keyboard, to enter a time of exactly 30 minutes before the actual time. This way a printout of 1400 hours and 20 ug/m^3 will occur at a real time of 1430, but the measurement will correspond to the average between the real times of 1330 and 1430. The printout of 1400, then, corresponds to the centerpoint of the actual time interval over which the 20 ug/m^3 measurement is representative. Obviously, this same rationale follows for $\frac{1}{2}$ hour printouts.

The instrument requires about a 3-hour stabilization time after a filter is inserted or changed. Once stabilization has occurred, the filter remains stable for its entire lifetime if the instrument remains on, continuously.

After a filter is inserted or changed, a prefilter at the air inlet can be used to observe the stabilization and then removed. Membrane filters of 1 μm pore size or less make satisfactory prefilters. Use as large a surface

area filter as practical (approx. 15 cm^2 or more) to provide as minimal a pressure drop as possible to the detector. (Connect several small ones in parallel, if necessary.)

Please note that when using a prefilter in front of the air inlet, the process of inserting or removing the filter will produce a disturbance to the oscillation of the TEOM detector. This means that the next reading following the insertion or removal of a prefilter may be erroneous and should be disregarded. Alternatively, if a prefilter is not used, one can just ignore the first three hours of data or simply introduce a start time 3 hours ahead, thereby preventing printouts for that period of time.

D. Filter Replacement

Filter life will vary depending upon the aerosol level. Typical lifetimes will be from days at modest aerosol levels to weeks at low levels. When the filter approaches the end of its usefulness, the LED display and the printout will show decimal points after each number. The decimal points may not show up with each data point but will become more and more frequent as the filter clogs. The filter should be replaced when approximately 50% of the data points show decimal points.

Changing a filter is very simple, and is done with the instrument still running.

1. Unscrew TEOM detector top ring.

2. Relieve vacuum by unscrewing pump thumbscrew on vacuum side counterclockwise.

3. Remove TEOM top plate.

4. Gently unscrew and pull old filter straight out. Filters mount on a conical support on top of the TEOM oscillating element (see Fig. 3). Do not break this element. Do not attempt to bend or produce any sideways motion on this element. Also note that the air deflector in the filter chamber is quite sharp, so use care with fingers.

5. Clean inside of chamber if necessary.

6. Insert new filter on tapered mount so that it gently seats. Do not apply force. Filters should not be deformed by this process.

7. Reseat '0' ring.

8. Replace top cap.

9. Screw on top ring. Do not over-tighten. Be careful not to unseat top cap while doing this.

10. Screw pump thumbscrew clockwise as far in as it will go.

11. Press blue button and perform keyboard entries from Step 3 through Step 7. It is necessary to do this every time a filter is changed, even if the entries are the same for some filters. This is due to the fact that the oscillation of the TEOM is severely interrupted during a filter change, and the microprocessor must be reset when a new filter is in place.

V. Additional Notes

1. Negative signs on the printout appear as C .

2. After the blue button is pushed and new constants are entered, the first printout will read zero.

3. Keep filters in closed vials with silica gel at all times. If the instrument is to be turned off while a good filter is still in place, remove the filter before the instrument is turned off and place it back into its vial.

4. The cyclone preseparator can be cleaned every few months by unscrewing the collection cup cover (located on the left side of the horizontally mounted cyclone opposite the TEOM side) and wiping it clean.

This unit is not weatherproofed.

FIGURE 1a.

Ambient Particulate Mass Monitor
(TEOM - Filter Unit)

See Figures 1b and 1c for detail.

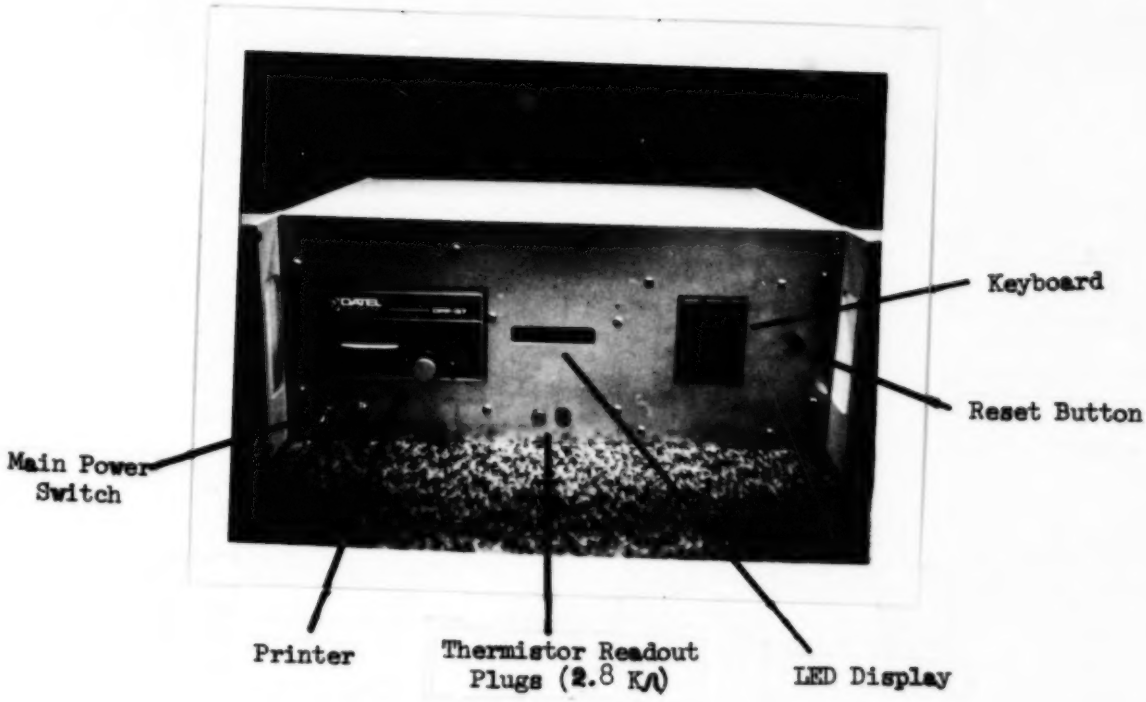

FIGURE 1b.
Electronics Package

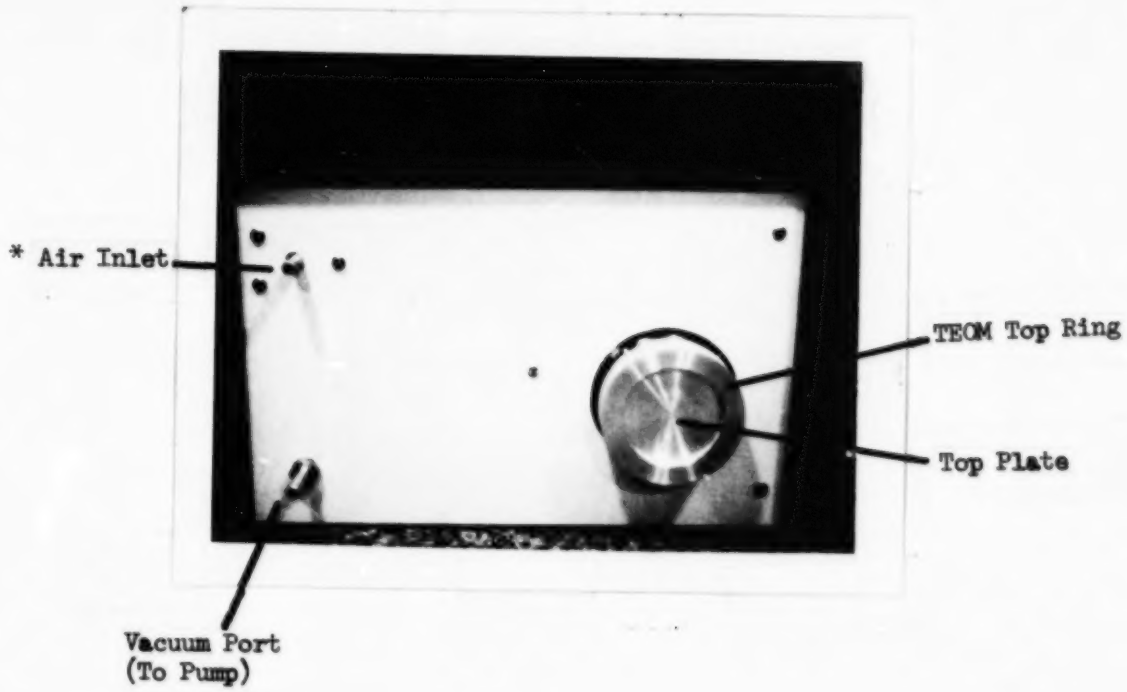

FIGURE 1c.
Detector Package

*In units equipped with cyclone preseparators, this inlet is mounted vertically on an extended tube on top of the detector package.

FIGURE 2
Inside of Detector Package

*In units with a preseparator, a cyclone is located in this position. In this case, the cyclone inlet tube and the cyclone itself are both heated.

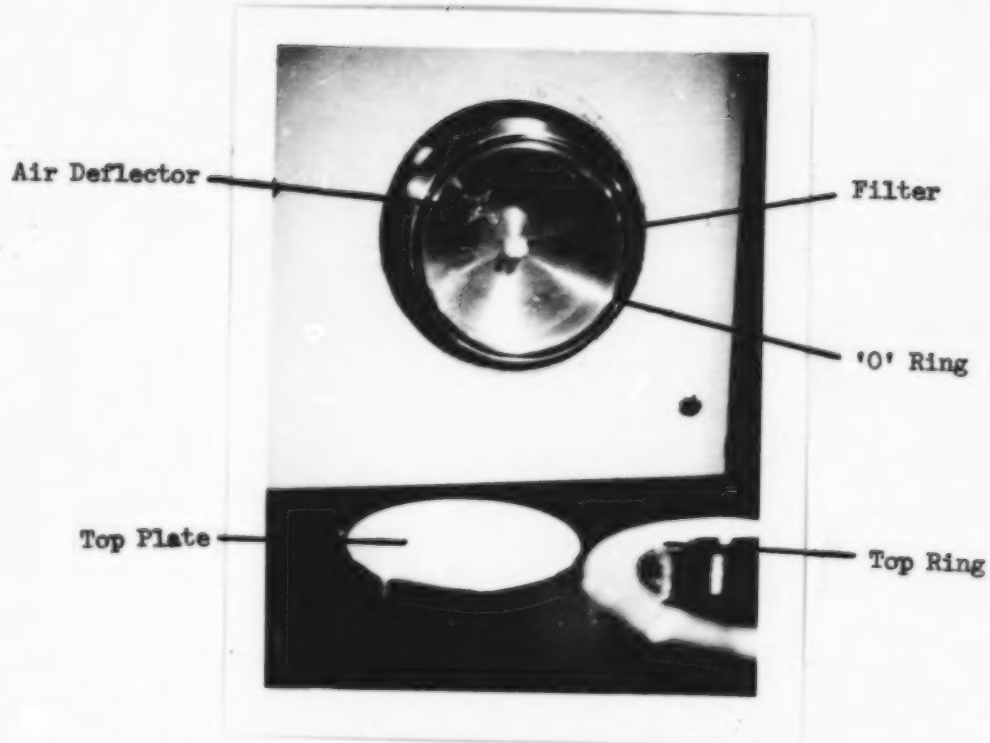

FIGURE 3
Filter Chamber